Evaluating the Residual Risks of Infusing New Technologies into NASA Missions

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SUMMARY & CONCLUSIONS

NASA's need to infuse new technologies into its missions has been described. Some of the challenges associated with new technology infusion, and a way to meet those challenges, have been presented. The Technology Infusion Guideline (TIG) process has been described as well as the Defect Detection and Prevention (DDP) process that is the underlying evaluation 'engine'. An example of this evaluation on one of NASA's technologies under development has been presented. This example is used to illustrate the generic process.

The results of implementing the TIG process on the example technology clearly demonstrates that the TIG process can penetrate to underlying technical details to evaluate the viability of continued technology development resources. The technology evaluated was deemed 'on the right track' and critical to NASA's future missions needs. The TIG process results in a technology infusion roadmap, or prioritized set of activities which must be performed to address the identified residual risks. These activities include alignment with other parallel technology development work, specific characterization and testing, breadboard development and miniaturization and ruggedization. The return on investment for implementing this process has been measured at over 20:1 with significant schedule savings. The risk reduction as a result of implementing this process will only be directly measurable after the technology matures to a greater extent.

3.1 *INTRODUCTION*

It has been widely recognized that a "gap" exists between our efforts to develop our advanced technologies, and the efforts by the more "focused" flight projects and missions, to use them. Infusion rates suggested by a recent survey which looked at a random sample of technology "pull" situations, indicate that once a product has reached proof-of-concept, it stands a less than 50 percent chance of infusion into a flight system. We would expect products to "die on the vine" at lower Technology Readiness Levels (TRL) where product viability is by nature of early R&D, unknown. However once product viability has been demonstrated, we have traditionally assumed that the remaining "engineering" work needed to make the product useful should be doable in a project/mission environment. What we see instead is that overlooked failure modes (show stoppers), undetected earlier in the product validation phase, surface at the worst possible time when projects are counting on the technology to be ready in time for their mission.

This has led us to develop a new way of handling these risky technologies which involves engaging a small team of multi-disciplined "experts", from a wide variety of fields, to "trouble shoot" the technology well before a project engages to use it. We believe that spending serious attention to each product nearing proof-of-concept, and assessing its potential failure modes, against a set of real, or representative, mission requirements, and then applying risk mitigation techniques (all in a weighted fashion), will clearly roadmap the technology into a customers application. This will eventually improve the technology infusion rate of NASA products which is the primary metric used to judge the success of this process.

The underlying motivating reason, for spending time (and not an insignificant amount of money) on the infusion problem, is that we want to protect NASA's technology investments which become threatened when new NASA technologies are not infused successfully in this "Faster Better Cheaper Safer" era.

3.2 *PROCESS FOR IMPROVING INFUSION RATES*

Infusion rates for technology* have significant room for improvement. An informal survey has revealed that the predominant reasons include miss-communicated customer requirements, non-flight worthy technology (i.e. stopped by engineering issues not technology issues) and technologies which were replaced by nearly equivalent commercially available technologies. Thus, the problems could be addressed by clear definition of customer requirements, early focus on engineering difficulties that result from particular technology architectural decisions and a clear understanding of where competing technologies will be at the time of delivery.

To address these infusion rate challenges, the Defect Detection and Prevention (DDP) methodology[1,2] is being utilized as the 'engine' of the TIG process. The DDP process can be summarized as:

Assess the impact of potential, relevant failure modes to determine how much each failure mode affects requirements (identifies tall pole failure modes):

1. Identifying customer requirements for the technology being evaluated (e.g. survives 100krad, operates over –25 to +125C, is painted blue)
2. Evaluate failure modes for the given technology, assess which requirements they impact, and weighting the impact of a given failure mode on a given requirement (e.g. % of a given requirement lost if the failure mode occurred)
3. Assess all identifiable **P**reventative measures, **A**nalysis, process **C**ontrols, and **T**ests (PACTs) and weight the effectiveness of a given PACT on a particular failure mode (e.g. chance of failing to detect or prevent the failure)
4. Balance the risk.
   — Determine which risk issues are pure technology issues, determine PACTs that will/will not be performed to mitigate the risk.
   — Identify risk issues are engineering issues clearly not on the roadmap to a viable technology demonstration.
   — Determine which risk issues are a combination and for which co-project funding will be sought.

Steps 1 & 2 produce a failure mode impact chart that is shown for the example technology later in this report (Figure 4). Step 4 produces a failure mode impact chart (the final Risk Balance) which is shown for the example technology later in this paper (Figure 2).

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* Infusion rates are defined as the ratio of the number of technologies still manifested on a given mission after CDR and the number of technologies which achieved Proof-of-concept.

3.3 *EVALUATED TECHNOLOGY*

Compact, holographic data storage (CHDS) has the potential to revolutionize data handling and storage for NASA missions. With their large storage size, non-volatility and fast transfer rates, it appears that these data storage technologies can meet the demanding needs of the 21st century. These memories imprint materials with holograms which result from interfering the signal beam with a reference beam[3,4,5,6]. The signals are then read out by reapplying the reference beam to the storage medium. There are a number of ways of generating a signal beam but most involve conversion of analog to digital data which then generates a spatial distribution of ones and zeros which then results in an interference pattern which is then imprinted in the material. There are a number of references available for the different methods of imprinting[7,8] but all essentially involve changing the electronic distribution of the storage medium[9,10,11,12]. In an effort to better understand the overall CHDS system, the TIG team generated (with the help of the technologist) a preliminary block diagram which was used (and updated) throughout the evaluation process.

3.4 *SUMMARY OF THE EVALUATION*

As shown in Figure 1, the TIG process applied to the CHDS identified 42 requirements, 93 failure modes, and 99 PACT options. The requirements are a combination of high-level mission requirements (e.g. environmental) and functional requirements specific to a data storage and retrieval technology (e.g. access time). The failure modes, or risk elements, were initialized by the technologist and augmented by the TIG team. The final set covers all disciplines associated with the CHDS technology – they range from electrical buss issues to LiNbO3 defect properties. The PACT options are a mixture of those most likely to be required for the flight build, possible characterization or diagnostic activities, and those that were originally planned.

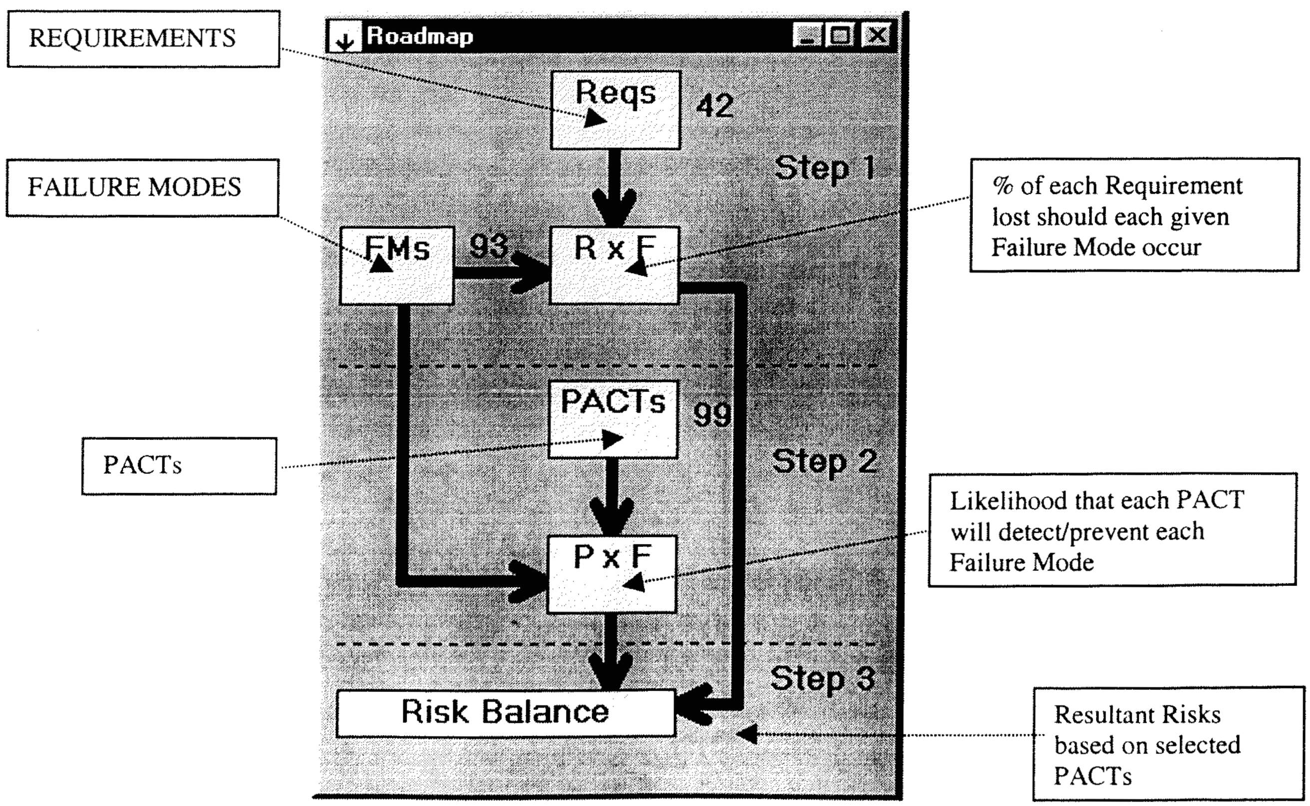

Figure 1 Graphical depiction of the DDP process

The process generates the driving requirements (See REQUIREMENTS below) as those which are at the most risk of impact by unmitigated Failure Modes (See RISKS ELEMENTS below). The process also generates a pareto diagram (bar chart) of the Failure Modes ranked from mist critical to least critical. These Failure Modes are also dispositioned as to whether they are Technology (fundamental to the technology), Engineering (implementation issues associated with flight preparation), or both. As a result of the selected PACTs (See PACT OPTIONS below), the Risk Balance is then obtained. The bar chart depicted in Figure 2 depicts the residual risk (See RESIDUAL RISK below) after application of the selected PACTs and is intended to provide a big picture view of the risk landscape. One portion of the process systematically looked at the resultant risk and added (or subtracted) PACTs to ensure that the technology development activities focused on those technology areas of most concern.

Some general notes regarding the Risk Balance figures are in order first:

1) The plots are all LOG SCALE (the plots range over 6 orders of magnitude)
2) The total original heights of the bars (i.e. that risk that would result from the application of no PACTs) are shown in green and referred to as "UnPACTed"
3) The non-green risks are those which result after the application of the selected PACTs. These have been dispositioned into pure technology issues, pure engineering issues, or some combination of both.
4) The failure modes have been numbered for easy reference.
5) The charts are usually 'sorted' to represent the failure modes in the order of remaining risk.

The final results of the evaluations are shown in Figure 2 below. While nearly all of the risk elements have been reduced (Green shows the original risk), note that the 'tallest poles' have now become predominantly engineering and engineering/technology issues. The technology-only issues have been moved to the right (i.e. had their risk reduced relative to those issues on the left). The remaining tall pole technology issues are primarily radiation and contamination susceptibility related.

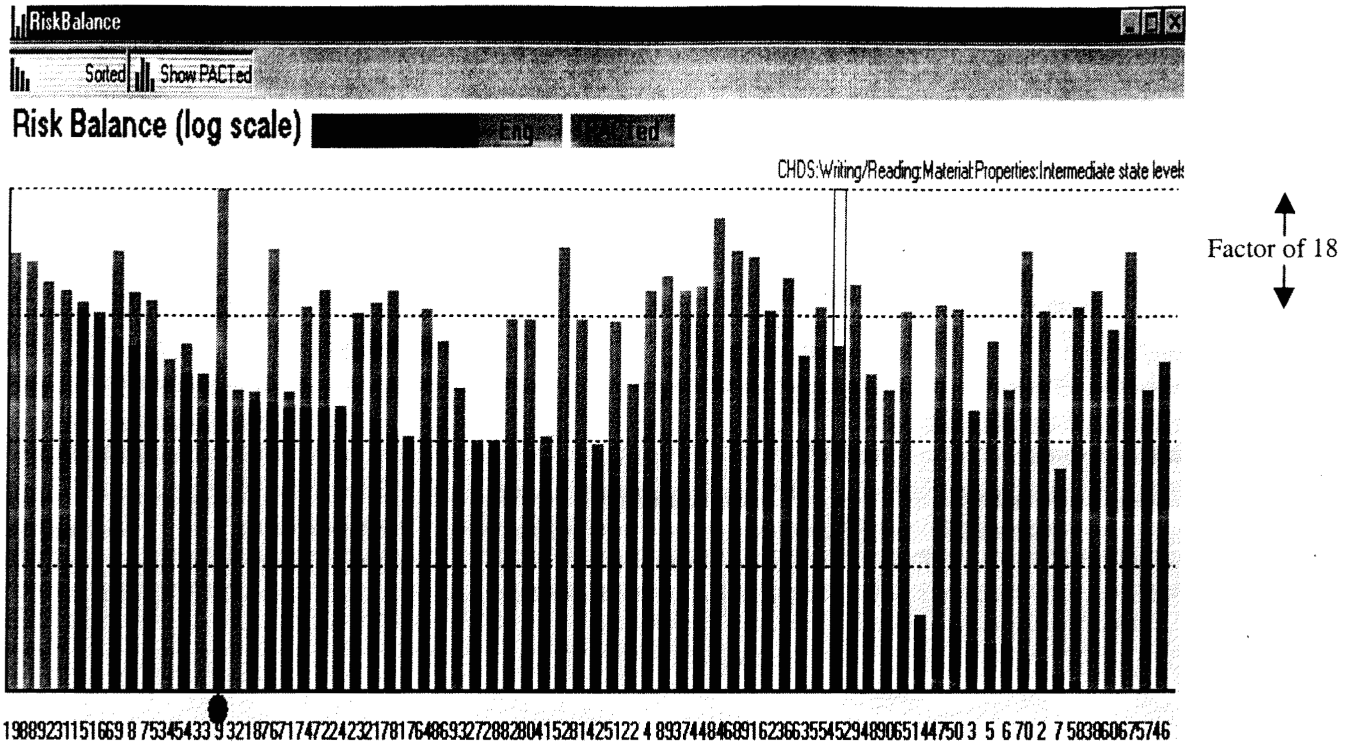

Figure 2 Graphical summary of the TIG evaluation for the CHDS. The numbers correspond to the various Failure Modes identified (See RISK ELEMENTS). Note that the plot is a log scale with a factor of 18 between each of the abcissa grid lines.

Note that the results of the evaluation (with the PACTs that were selected) reduces the technology risk elements and leaves a particular set of environmental effect (FM 15 and FM 16) issues as the tallest poles. The next tallest poles are a particular performance issues (FM 76) and some environmental exposure issues (FM 72 and FMs 21, 23 and 24). Further discussion of these results are found in the following Section.

3.5 *DETAILED RESULTS OF THE EVALUATION*

As described above, the DDP process utilizes Requirements, Failure Modes, PACTs and their inter-relationships to produce the final risk balance. The tool used is very graphical in nature with descriptions 'popping up' depending on the location of the cursor. For a report, it is important to use a scheme to allow easy referencing of items under consideration - thus the Requirements, FMs, and PACTs are all numbered for easy reference. This numbering is carried onto the various bar charts and will always have a corresponding 'look-up' table to allow easy referencing.

There are also some general comments regarding the outputs which are useful to facilitate understanding. First of all, there are 'tree structures'[†] for Requirements, Failure Modes and PACTs. These tree structures are primarily used as organizational tools, that is to make it easier to find a particular piece of information. However, in Failure modes they may also be logically

[†] In discussing trees, it is common to use genealogical referencing, e.g. the parent of a FM is that FM which is one higher place up on the tree.

related (much like a Fault Tree) in which all 'children' of a Failure Mode may have the same effect as the 'parent' FM.

5.1 REQUIREMENTS

For a typical low TRL technology, the customers are, in general, programs or classes of missions. For the CHDS, the customer base includes Outer Planet missions with extensive data storage requirements and volatility concerns as well as Earth Orbiting Hyper-spectral instruments. The next page provides a list of the requirements used during the evaluation with the various customer-defined weights shown. Note that the greater the weight the more important a FM which impacts it will be. Also note that if a 'parent' FM has a given weight, it's 'children' get portions of that weight allocated to them according to their weights.

The results of the evaluation also indicate which requirements are the 'drivers', so that a customer can be sure that these requirements are really necessary, and similarly requirements which were not 'driving' may be able to be more demanding with little penalty. This summary of the 'driving' nature of the requirements is shown in the following Figure. Also, note that the extent to which the requirement still remains at risk is also shown (in red).

Driving Requirements: The requirements which are most driving the CHDS failure mode importance can be obtained directly from the figure and are: Bit Error Rate, Mission Duration and Storage size. These have been protected by PACT application but still leave Mission Duration=5 years, BER < 10^-8 and a variety of environmental requirements as the requirements most at risk. However, most of the residual risks in these areas are now (after the evaluation) primarily engineering issues.

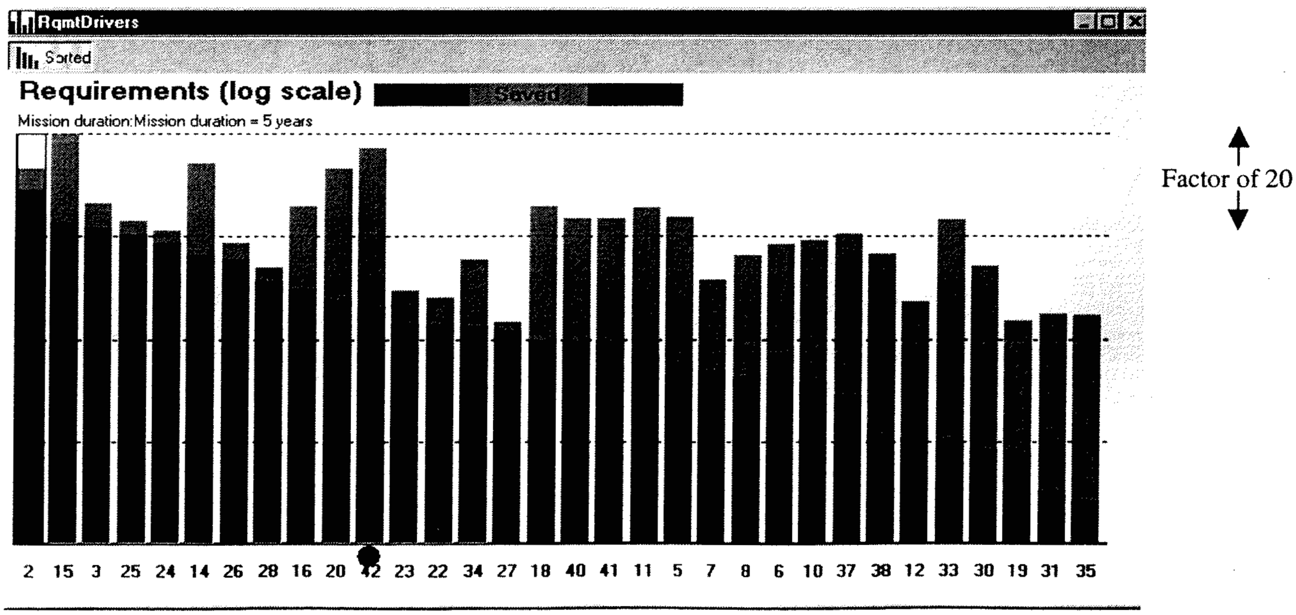

Figure 3 Requirement drivers for the CHDS. Note that the requirements have been sorted on the extent to which they still remain at risk following the application of the planned PACTs.

5.2 RISK ELEMENTS

The TIG evaluation included a collection of discipline experts who provided insight into a wide variety of potential failure modes. These potential failure modes, or risk elements, range from system issues to particulars about the storage medium. They include system issues (e.g. refresh power, volume), environmental exposure effects (e.g. radiation, launch vehicle, contamination), ground exposure (e.g. ESD), a variety of performance issues associated with the individual CHDS components, some issues unique to the storage, reading or writing steps, and some associated with the associated peripheral electronics.

While the evaluation was intentionally focused on the technology as it exists today and in the near-term, one of the purposes of the TIG evaluation team is to look forward to flight and anticipate issues which might arise. Many of these issues are beyond the scope of the current CHDS development effort and are intended to provide a basis for discussion with potential users of the technology. However, some of these issues require some evaluations, tests or analyses to determine susceptibility in order to ensure that no 'show stoppers' await in the near future (See CONCLUSIONS).

These potential Failure Modes were then dispositioned into Technology, Engineering or both. After evaluating the impact on the various weighted requirements, the FMs can be ranked according to potential impact as shown in Figure 4. This impact is scored by estimating the extent to which the requirement will be impacted should the FM occur and can range from 0 (no impact) to 1 (complete loss of requirement).

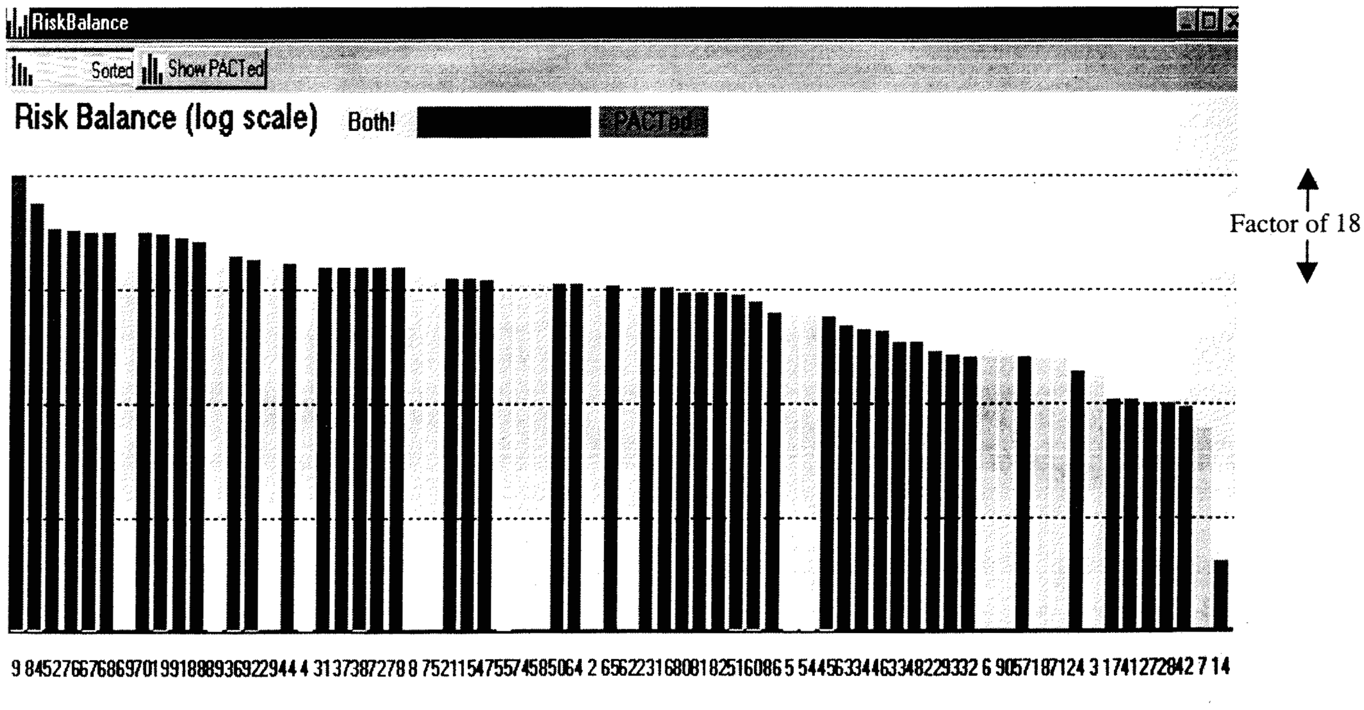

Figure 4 Failure modes before application of any PACTs. Note that the technology issues are some of the 'tallest poles'. After application of PACTs, most of these drop and move to the right.

5.3_PACT OPTIONS

Now that the risk elements have been identified and prioritized, the process next evaluates the effectiveness of a variety of PACTs (or mitigation options). As one applies a PACT, the effectiveness at preventing (or detecting) the occurrence of a given failure mode is scored. The scoring ranges from 0 (no possibility of detection/prevention) to a 1 (absolute certainty of detection and prevention). In practice, the more specific the FM, the more accurately the effectiveness can be estimated. For high-level, or rolled-up, FMs the effectiveness scoring uses a 0.1, 0.3 or 0.9 to represent low, medium and high effectiveness. As additional information is available, these base scores are modified.

The process began with the set of PACTs already planned by the technologist and during the course of the TIG process, others were immediately identified as good ideas and selected. Others were still scored although not necessarily selected at that time. Finally, the process concluded with 'risk balancing'. This entails using the tool to examine the residual risk and allowing the tool to present options for PACTs which could be selected to further reduce the risk. The final list of selected PACTs ranged from preventative measures such as adhesive selection and anti-reflection coatings, to analyses such as jitter and wavelength sensitivity, to tests such as optical verification and breadboard operation.

5.4 RESIDUAL RISK

After completing the process, the residual risks may be plotted (See Figure 5) and it is seen that the 'tallest poles' are predominately engineering, or both (as opposed to technology only).

Note that the selected PACT options have reduced the Technology issues to the right and the overall risk has dropped. Note that some of these PACTs also had some limited effectiveness on pure engineering issues which is the reason for the risk reduction for engineering-only failure modes. A summary of the numerical values which are represented in this bar chart may be found in Appendix 3, in which each FM is listed with it's before and after impact, as well as the list of the PACTs selected and those which could have had some effectiveness but were not selected.

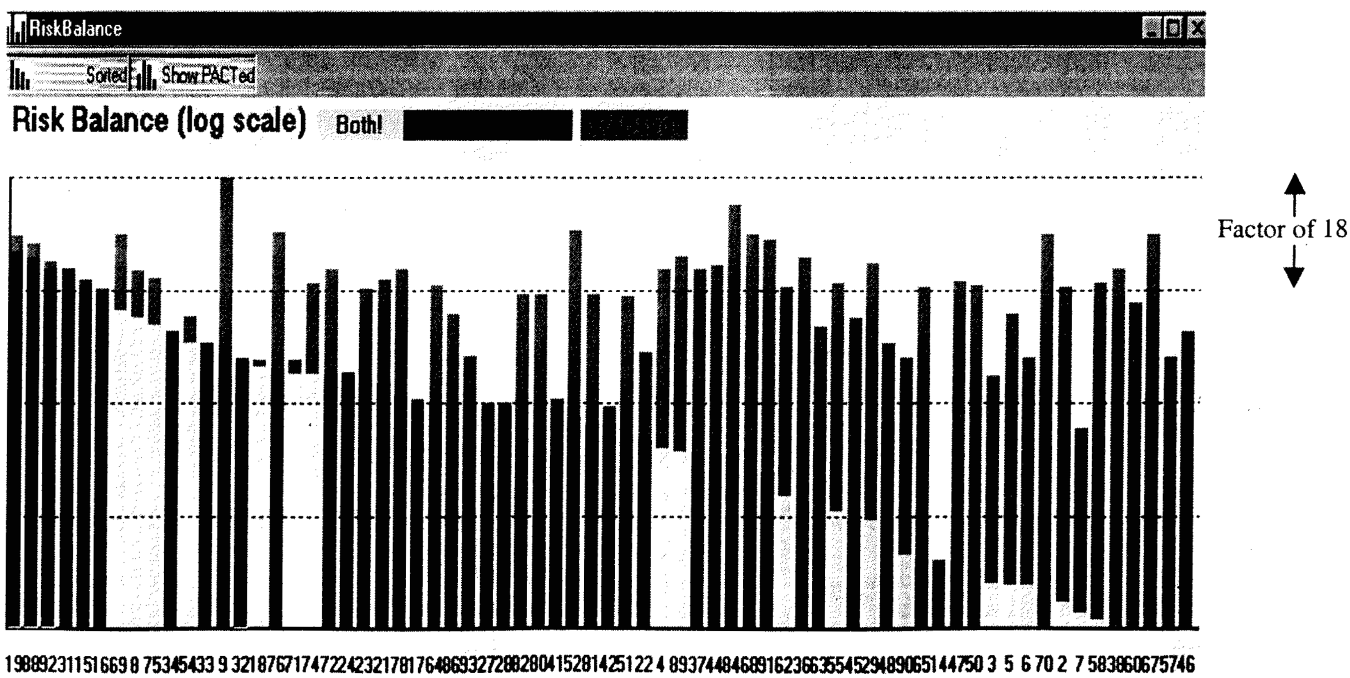

Figure 5 Final Risk Balance for the CHDS technology. The failure modes are numbered (single and two digit) for reference to listing in RISK ELEMENTS.

6. A LOOK TO THE FUTURE

Once breadboard proof-of-concept has been achieved, real-time memory recording and reading will have been demonstrated, and the development will take on a more "engineering" appearance. Advanced packaging techniques, electronics design and optics issues, special coatings and adhesives, etc. are identified in this report and will be addressed as customer requirements become more clear. Addressing these engineering or engineering/technology issues will be a joint effort with the customers and co-funding arrangements will need to be planned over the course of this.

7. APPLICABILITY

Although the process described has been applied to technology for NASA's future missions, the general applicability of the process appears unlimited. Every new technology has requirements, risk elements and PACTs.

ACKNOWLEDGEMENTS

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